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**PHOTO-INDUCED DICHROIC POLARIZERS**  
**AND FABRICATION METHODS THEREOF**

**FIELD OF THE INVENTION**

This invention relates to methods of fabricating polarizers from dichroic materials, and to polarizers fabricated by such methods. In particular, the invention relates to photochemically stable dichroic molecules and the device structures, which are suitable for the fabrication of thin light polarizers.

**PRIOR ART**

Light-polarization films or polarizers are major components liquid crystal displays (LCDs) and other liquid crystal (LC) devices. Commercial polarizers are usually based on polyvinyl-alcohol-iodine (PVA) films of 150-400 $\mu$ m thick. These polarizers are generally placed on the external glass surfaces of the LC cell and require protective films (e.g. cellulose triacetate or cellulose acetate butyrate). The fabrication of such known commercial polarizers is rather complicated and expensive. Recently, to improve the cost-effectiveness, there are have been proposals to fabricate the light polarizers by printing or photo-alignment technologies.

In U.S. Patents No 5,739,296 and 6,049,428, polarizing films are formed from dyestuffs, which have stable lyotropic liquid crystalline phases in a wide range of concentrations, temperatures and pH-values. In a sheared flow, the lyotropic liquid crystal molecules are self-assembled and oriented preferentially in connection with the flow direction. When the proper preparation conditions are met, a well ordered solid phase of the lyotropic liquid crystal is formed. In certain cases, the order parameter as a

measure of this alignment effect is high, so that this material is suitable for the fabrication of polarizers. To create this sheared flow, rollers and blades have been suggested.

To minimize any defects due to the shear flow alignment, a photo-alignment technology to prepare the thin photo-patterned polarizer has been proposed [V. Kozenkov et al, SID'00 DIGEST, p.1099]. Since this is a non-contact method, the particulates and static charges generated can be in principle eliminated. In addition, the cross contamination problems can be minimized. With a birefringent mask, this technique makes the fabrication of multi-domain structures more cost-effective for the wide viewing-angle LCD applications

#### SUMMARY OF THE INVENTION

According to the present invention there is provided a method of forming a polarizing material comprising the steps of: (a) forming a layer of a dichroic material on a substrate, and (b) exposing said layer to activating light illumination to provide an ordered structure with a distinguished absorption axis. Preferably the layer may be polymerised.

Preferably different regions of the polarizing material are polarized by activating radiation with different polarization axes so as to produce regions of said polarizing material with differing axes of polarization. This may be achieved by regions of the layer being exposed independently by the use of masks to isolate selected regions for exposure. Alternatively a birefringence mask may be used to create activating radiation with a selected spatial distribution of polarization vectors.

In preferred embodiments the layer may be provided with a coating (eg iodine) to change its spectral response. If different regions of the layer are formed with different coatings a multi-color polarizing material may be produced.

A stack of layers may be formed on a substrate with the layers being separated by isolation layers.

The activating radiation is polarized or non-polarized, but directed and may be a continuous waveform or may be pulsed. The polarization of the dichroic layer may be controlled by varying parameters selected from the group consisting of the incident angle of the activating radiation, the exposure energy density and the process temperature.

According to the present invention there is also provided a polarizing material comprising a layer of a photochemically stable dichroic absorber. Preferably the absorber is formed within a polymer matrix.

The dichroic absorber may be selected from the group consisting of: mono-, bis-, tris-, and poly-azo dyes, quinone dyes, mono- and poly-oxyanthraquinone dyes, sulfur-substituted hydroxythio-anthraquinone dyes, aminohydroxy-anthraquinone dyes, anthrapirimidinone dyes, merocyanine dyes, azomethine dyes, polycyclic compounds, benzoquinones, napthoquinones, tolanes, diphenyls, p-nitroanilines, p-nitrosodialkylanilines, dialkylaminostyroles.

The polymeric materials may be selected from the group consisting of: polyimide, polyethylene, cellulose acetate, polystyrene, polycarbonate, polyester, polyacrylonitrile, polyacetal, polyacrylamide, polybutadiene, polyvinylalcohol, polymethylmethacrylate, and polyvinylcinnamate.

The polarizing material may be provided with a coating of a material (eg iodine) selected to alter the spectral response of said material.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Some examples of the invention will now be described by way of example and with reference to the accompanying drawings, in which: -

Fig.1 shows the transmittance of an azodye film during the pumping (a) and the dark relaxation (b), the molecular transformation is pumped by a laser beam of about 100mW/cm<sup>2</sup> at 488nm or 514nm, whereas the signal is probed by a 0.2mW-633nm laser source,

Fig.2 shows the absorption spectra of the exposed azodye film,  $A_0$  represents the absorbance before the illumination, and p and s are the suffixes of p- and s-waves,

Fig.3 shows the transmission spectra of the exposed azodye film before (a) and after (b) treatment with iodine,

Fig.4 shows an embodiment of the invention in the form of a multi-layer structure,

Fig.5 shows an embodiment of the invention with a polarizer having areas of different polarization axes,

Fig.6 shows another embodiment of a multi-axes photo-induced polarizer,

Fig.7 shows embodiments of the invention with multi-colour structures, and

Fig.8 is an illustration of induced optical anisotropy when an azodye layer is illuminated obliquely by a polarized or non-polarized but directed light.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Before describing a number of embodiments and examples of the present invention, it would be useful to define a number of terms to be used in this specification.

By "anisotropically absorbing molecules", reference is made to compounds with anisotropic geometry, such as rod-shaped or disc-shaped, which exhibit absorption properties with different values along different axes. For example, dichroic compounds and lyotropic liquid crystal compounds are anisotropic absorbers.

By "linear polarized light" is meant light that is polarized mostly along one axis (the major axis) of a plane orthogonal to the propagation direction.

The term "photochemically active molecules" refers to molecules that are involved in irreversible or reversible photochemical reactions. In the solid phase, the quantum efficiency associated with the photochemical reaction is about 0.1-1.

The term "photochemically stable molecules" refers to molecules that are no longer involved in the irreversible or reversible photochemical reaction. In the solid phase, in such cases the quantum efficiency associated with the photochemical reaction is about  $10^{-8}$ -0.1.

The term "photostable molecules" refers to cases where the quantum efficiency associated with the photochemical reaction is less than  $10^{-8}$ .

By the term "photo-anisotropic medium" (PAM) is meant that the isotropic solid phases of photochemically active, photochemically stable and photostable molecules exhibit photo-induced anisotropy (absorption dichroism and birefringence), upon the absorption of polarized or non-polarized photons. The induced anisotropy is associated

with the direction of polarization vector, the incident angle and exposure energy of the light illumination.

The term "substrate" refers to any medium able to support the formation of thin surface layers of PAM for example. A substrate can be any solid combination of layered materials. The materials can be any combination of glass, silicon, oxides, plastics and metals. In particular, silver, gold, aluminum, polyimide, silicon monoxide, indium-tin-oxide, silicon dioxide, and color filter layers are common examples.

As will be seen from the following description of preferred embodiments and examples, the present invention provides photo-induced polarizers formed of dichroic materials. In particular, as can be seen from Fig. 1(a), when the dichroic molecules are exposed to a low power actinic radiation, long-lasting optical anisotropy and dichroism are photo-induced.

There are two major types of physical mechanisms, which give rise to the photo-induced phenomena. The first is based on irreversible photo-chemical reactions, such as photo-induced cross-linking and photo-decomposition. The anisotropic layers formed in this way are characterized by a small value of the order parameter (<0.4) and the corresponding low value of the induced optical anisotropy and dichroism. The order parameter is very sensitive to the exposure time and chemical content of the substance and has to be accurately controlled. Moreover the contamination of the initial substance by the by-products of the photo-degradation is possible in certain cases. The dichroic spectra of these substances considerably change its form during the exposure. All these disadvantages prevent the application of the absorbing layers, formed by photo-chemical mechanism as dichroic polarizers.

The second mechanism is based on the reversible *cis-trans* isomerization and Weigert effect, i.e. Brownian motion in a potential field of the actinic light. The probability  $\varepsilon$  of photo-absorption is proportional to the square of cosine angle between the polarization vector of actinic light  $E_{hv}$  and the vectorial absorption dipole  $\mu_{ge}$ , i.e.  $\varepsilon \sim |\mu_{ge} \cdot E_{hv}|^2$ . In other words, the molecules that have their transition dipole moments parallel to the direction of the polarized light will probably undergo the conformational molecular changes. Consequently, these will lead to a non-uniform distribution of molecules. However, with this mechanism when the pumping light source is removed, the molecules and domains relax slowly (Fig. 1b). The order parameter as a measure of these photo-induced effects can be very high in some dichroic materials, but since these are reversible processes, blending with a polymer matrix or polymerization to form a network is preferable so as to fix the alignment against any thermal or photo perturbation. Therefore, a polarizer can be produced by this clean and non-contact method. In addition, the fabrication methods for multi-layers, -axes and -colour photo-induced polarizers based on the same dichroic materials are described in the following. The polarizers and the polarizer fabrication techniques described in this specification are all compatible with current LCD manufacturing techniques.

The photo-induced optical anisotropy of PAM takes place due to the orientational molecular ordering. The major axis of induced anisotropy is perpendicular to the direction of polarized activating radiation. It will however be parallel to the plane of incidence for the non-polarized actinic radiation. Some of the photochemically stable substances give rise to the high molecular order parameter  $S > 0.8$  and are thermally stable up to the melting temperature of the substances. In some cases, the corresponding

temperature is 140°C-180°C. In addition, the spectral absorption changes of these substances are not noticeable.

The PAMs materials can be based on photostable organic compounds and dichroic dyes with an anisotropic absorption either in UV-, visible or IR- spectral region in the range between 200 and 2000nm and, in particular, in the visible region between 400 and 800nm.

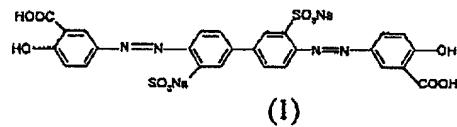
These substances belong to the following dye groups: mono-, bis-, tris- and poly-azo dyes, metal-complex azo dyes; quinone dyes; mono- and poly-oxyanthraquinone dyes, sulphur-substituted hydroxythio-anthraquinone dyes, aminohydroxy-anthraquinone dyes; anthrapirimidinone dyes; merocyanine dyes; azomethine dyes; polycyclic compounds; benzoquinones and naphthoquinones; tolanes; diphenyls; p-nitroanilines, p-nitrosodialkylanilines; dialkylaminostyroles etc. Besides, these substances can have bi-functional reactive groups, which polymerize by thermal or photo treatment to form a polymer network. Alternatively, these substances can be introduced as the chromophores in the polymer matrix. Some examples of the polymer matrix are polyimide; polyethylene, cellulose acetate; polystyrene; polycarbonate; polyester; polyacrylonitrile; polyacetal, polyacrylamide; polybutadiene; polyvinylalcohol; polymethyl-methacrylate; polyvinylcinnamate. In both cases, the thermal, optical, electrical and mechanical properties can be improved. Usually the concentration of the substances in the polymer matrix does not exceed 5-15 wt/wt% so that the final thickness cannot be too thin however. The additives, which promote good adhesion, suitable viscosity and low curing temperature, can also be introduced.

Various methods can be used to put the PAM layer to the substrate, including spin-coating, dipping, spraying, brushing, printing, Langmuir-Blodgett technique and thermal evaporation in vacuum.

The following examples demonstrate the device structures, fabrications and applications of the photo-induced polarizers using the PAM materials. The PAM layers, obtained in the following examples, can be deposited on rigid or flexible substrates.

**Example.1.**

A thin film of the following azodye (1)

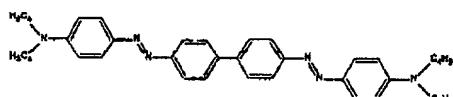


is prepared by the method of vacuum sublimation at pressure of about  $2 \cdot 10^{-5}$  mm Mercury. The deposition temperature onto two glass plates is 20°C. The melting temperature of the azodye is 146°C. The deposition rate is 0.93nm/sec and the total deposition time is 4.5 minutes. The final thickness of the azodye layer is 0.25 microns. During the deposition process, one of the glass plates is *in-situ* exposed to a linearly polarized light. The light is generated by a 250-Watt Mercury lamp with peak wavelength at 546nm and the power density is 22.3 mW/cm<sup>2</sup>. The same polarized light exposes the second glass plate after the azodye layer has been formed. It is found that the photo-induced optical retardation of the azodye, which is measured at wavelength 632.8 nm, is

equal to  $\lambda/12$ . This is significant for many display applications. The energy densities for the first and second glass plates are about  $4.1 \text{ J/cm}^2$  and  $12.7 \text{ J/cm}^2$  respectively.

**Example. 2.**

Another useful azodye (2) is shown below.



(2)

To prepare the PAM layer, 1-10wt % solution of the azodye in chlorobenzene is spin-coated on a glass substrate at room temperature. This solid dye film is then irradiated at normal incidence by a polarized UV light. The light source is a 1000 W Oriel Xenon arc lamp. The UV sheet polarizer is purchased from Oriel Instruments. The intensity of polarized UV light at 365nm is about  $6 \text{ mW/cm}^2$ . The energy density is about  $10.8 \text{ J/cm}^2$ . In Fig.2, the absorption spectra of azodye (2) are shown, and the order parameter calculated in this case is 0.86. Fig.2 shows the absorption spectra prior to exposure to polarized light (Ao) and of the p (Ap) and s (As) waves respectively after exposure to polarized light. The high absorption of the p wave in contrast to the s wave shows that the azodye layer is effectively polarized.

**Example. 3.**

The azodye layer can have a top coating of iodine or alcohol molecules. Such a coating may change the spectra of the dye making it more useful for applications in the visible

light range. Fig. 3 shows the transmission spectra of the azodye (2) before (a) and after (b) the treatment with iodine. The exposed PAM layer is prepared in accordance with Example 2, and then the iodine molecules are evaporated at room temperature and atmospheric pressure. The film thickness of iodine molecules has been measured in a control experiment. In the present example, a thin film of about 20nm is deposited on top of the exposed PAM layer. The coated layer is stable against the ambient light and low power laboratory lasers.

#### Example 4.

To optimise the extinction ratio and optical transmittance, a multi-layers structure may be formed as shown in Fig.4. The exposed PAM layer, which has a top coating of iodine, is prepared in accordance with Example 3. However, the thickness of the PAM layer and the top coating are reduced accordingly. To isolate this coated layer from each other, a thin layer about 10nm of polymer such as polyvinyl-alcohol is thermally evaporated onto the iodine layer. This embodiment of the invention improves both the optical and mechanical properties of the resultant polarizer.

#### Example 5.

The preferred orientation of the dye molecules and consequently the direction of the polarization axis can be independently varied in different surface regions. The sizes of these regions may vary from several microns to tenths of centimeters. Fig.5 shows an embodiment of the invention in the form of a multi-axis photo-induced polarizer, which has different local polarization axes in different regions. A dichroic layer 2 is formed on a

substrate 2 and is divided into a plurality of regions 3. Each region 3 is exposed selectively by polarized light in order to induce the polarization shown by the polarization axes 4. The different regions may be formed by masking the remainder of the azodye layer and subjecting a selected region to a particular form of polarized light. Each region may thus be polarized in turn. Fig. 6 provides another possible realization of the multi-axes polarizers. Fig. 6 shows the result of illuminating a plate bearing a dichroic layer with axially polarized light and allowing the plate to rotate. This creates the polarization distribution shown in Fig. 6. Because the dichroic layer will be polarized in a direction perpendicular to the axis of the polarizing light, the rotational movement of the plate results in circumferential polarization. The photographs in crossed polarizers illustrate the corresponding distribution of the intensity variations.

#### Example 6.

The absorption bands of the dye molecules and consequently the colour can be independently varied in different surface regions. The sizes of these regions vary from several microns to tenths of centimeters. Fig. 7 (a) and (b) show the multi-colour photo-induced polarizers, which have different local absorption spectra in different regions. In the figures the letters R,G,B and D stand for red, green, blue and dark respectively as examples. This can be achieved by applying different coatings to different regions in order to provide different spectral responses in the various regions.

**Example 7.**

The direction of polarization axis can be induced using the obliquely incident polarized or non-polarized light (Fig. 8). The optical anisotropy and dichroism depend on the exposure energy, incident angle and process temperature. This makes possible the uniform polarization direction on the curved surface (e.g. lens) or micro-objects with a surface relief profile (e.g. diffraction gratings).

It will thus be seen that, at least in its preferred forms, the present invention provides novel device structures and fabrication technologies for photo-induced polarizing materials. When the dichroic molecules are optically pumped by a polarized light beam, the probability of their transformation is proportional to the square of the cosine  $\theta$ , the angle between the transition dipole moments of the molecules and the direction of the polarized light. In other words, the molecules that have their transition dipole moments parallel to the direction of the polarized light will probably undergo the transformation. To minimize the dipolar absorption at the low power density regime, *cis-trans* isomerization and/or thermal diffusion in a potential field of the actinic light occurs and both lead to a non-uniform distribution of the molecules. In certain dichroic materials, these give rise to long-lasting optical anisotropy and dichroism that are able to polarize the light wave selectively. In a polymer matrix, this induced optical anisotropy and dichroism can be even higher and kept for a long time. This can also be accomplished if the dichroic molecules can be polymerized by thermal or photo treatment. Therefore, a permanent polarizer can be fabricated by a non-contact technique that basically requires an actinic radiation source. In preferred forms of the invention,

multi-layers, -axes and -colour polarizers using these dichroic materials are also possible and which may have applications, for example, for the wide viewing-angle LCD applications.